N91-24052

# Physical/Chemical Closed-loop Water-recycling

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## ABSTRACT

Water needs, water sources, and means for recycling water are examined in terms appropriate to the water-quality requirements of a small crew and spacecraft intended for long-duration exploration missions. Inorganic, organic, and biological hazards are estimated for wastewater sources. Sensitivities to these hazards for human uses are estimated.

The water recycling processes considered are humidity condensation, carbon dioxide reduction, waste oxidation, distillation, reverse osmosis, pervaporation, electrodialysis, ion exchange, carbon sorption, and electrochemical oxidation. Limitations and applications of these processes are evaluated in terms of water-quality objectives. Computer simulation of some of these chemical processes is examined.

Recommendations are made for development of new water recycling technology and improvement of existing technology for near-term application to life support systems for humans in space. The technological developments are equally applicable to water needs on earth, in regions where extensive water-recycling is needed or where advanced water treatment is essential to meet EPA health standards.

## INTRODUCTION

This report addresses minimum water quality requirements in terms of space mission needs. Means to achieve, assure and exceed that water quality are discussed. The fundamental approach is to adapt and extend established desalination and water-treatment technology to the special requirements of: (1) a high degree of water recovery (90% and more), (2) a small habitat, and (3) energy-efficiency.

A spacecraft, in a substantially closed-loop mode, may be treated as a microcosm of the open environment of Earth: the sources and uses of water are discrete, the pathways definable, and the reservoirs limited. As a closed system, a mass balance must be achieved, both for the water and for its solutes. The sources of used water for recycling will be identified first, then the water needs. The water-cycle options are thus limited, and a set of requirements for water quality and treatment is implied.

Desalination and other means of achieving the water quality required are then examined, with concern about technical and practical limitations of the methods and their appropriate applications in spacecraft. The recommendations for treatment yield another set of implications for water quality and implicate monitoring requirements to assure that the water remains satisfactory and to indicate repair or replenishment actions.

Susceptibility to hazards is rated by category:

1) Inorganic (e.g. corrosion contaminants),
2) Organic (e.g. detergents), and
3) Biological (e.g. viruses and microbes).

It is always preferable to avoid hazardous water contaminants (beyond normal uses), but this is not possible when contamination occurs:

1) from normal aging processes of the spacecraft: outgassing of plastics and normal corrosion, or
2) from accidental processes such as overheating of components, resulting in degradation of plastics and enhanced corrosion of metals, or
3) as residual viruses or other pathogens, including possible mutation of previously tolerated viruses during the flight, and the remote possibility of pathogens introduced from Mars.

One or more examples of performance of water purification systems can be created, based on reasonable choices of the water cycle, with the flows defined and the streams analyzed first by spreadsheet calculation of mass balances around the loop(s) for water and the major solutes and then by computer simulation (1) of the water treatment processes. Computer simulation allows rapid testing of the system's response under normal and abnormal operating conditions, and the simulation itself can be tested for validity by a few laboratory experiments.

## WATER SUBSYSTEM OPTIONS

Most of the sources and needs are the same as, or similar to, those projected for Space Station Freedom. However, for the longer Mars mission the transport cost of an accumulated shortfall (needs exceeding the recycled water) is greater.

## Recyclable water sources

Condensate - Condensate from the humidity-control condenser originates from human breath and perspiration plus evaporation from other water: showers, clothes-washing, etc. This source can hardly be expected to be free of viruses or bacteria of concern to humans. Though the crew in the closed environment clearly already have been exposed to air-borne infection, microbes could get out of control growing outside the body's active protections. An amount of corrosion contaminants and products of plastic (or lubricant) degradation is possible from the equipment in the ship.

Carbon dioxide reduction - A result of reduction of respired carbon dioxide by the Bosch or Sabatier processes is 1.15 to 1.8 pounds/person-day of water (2). This water may be added to the potable stream, since its source streams ($CO_2$ and $H_2$) are gas phases of purity at least comparable to cabin condensate, and is heat-sterilized — although ion-exchange protection against corrosion products is advisable.

Wash water - This waste water is from laundry-, shower-, hand wash-, and dish-water. It is clearly lower in quality than the condensate water. Measurable quantities of microbial, organic, and inorganic contaminants have been found and would be accumulated if not removed before recycling. Corrosion products from normal skin contact with equipment and tools are in this water.

Laundry water is the largest hygiene water element. It can be treated separately from the water used for washing people if different quality standards are applied for laundry use than for human contact. For the purpose of tracking constituents and testing input water assignments, it will be separated on a spreadsheet through the processing.

Urine - Studies for Space Station Freedom have demonstrated that potable water can be made from urine, using distillation and sorption. However, if adequate water of potable quality is available from a higher-quality source (lower solute and bacteria contents), there is no need to use recycled water from urine for other than laundry or electrolysis.

Waste oxidation - Oxidation of solid wastes, including wrapping materials, paper, tissues, fecal material, and hygiene aids, is a subject of another study parallel to this one. The useful result of the process of waste oxidation and reduction of formed carbon dioxide to carbon, of a waste of average composition $CH_2O$, is water. The amount is significant. From an estimated total of 2.2 pounds of waste or trash/person-day, more than one pound per person-day of new water is predicted. This provides an increasing reserve of greater than 2% of a person's requirements per day, potentially compensating for accidental or functional losses. This accumulation also offers the possibility that water needed by the Mars landing crew need not be returned to the spacecraft, conserving lift-off power.

| Sources | Hazard Estimates | | |
|---|---|---|---|
| | Inorganic | Organic | Biological |
| Condensate | slight | slight if filtered air | significant |
| CO2 Reduction | slight | very small | slight |
| Wash Water | significant | significant | significant |
| Waste Oxidation | corrosion possible | slight | slight |
| Urine | substantial (NH3+salts) | substantial | substantial |

## Water needs

Potable. - Potable water is needed for drinking, for food preparation (hydration and washing), for hygienic and medical uses where internal contact is expected (eye wash, brushing of teeth, occasional mouthwash and douches), and for possible other uses such as final rinsing of dishes.

Laundry - The largest single use of water is for washing clothes, over half of the "hygiene water" requirement. In an evaluation of U.S. Navy shipboard laundry-water recycling, moderate accumulation of organics and salts was tolerable through a recycling system containing flocculation, filtration, and activated carbon elements (3). A total organic carbon level of about 140 ppM was a steady-state condition. One would initially conclude that the water-quality standard for clothes-washing water may be substantially lower than that for potable water so the implications of partial purification are worth examination. These are: (1) Possible increase in use of carbon adsorbent. Since more organic material was allowed in the laundry-recycle water, passage through carbon adsorbent would be expected to remove more material and more rapidly exhaust the adsorbent, and (2) Possible increased use of bactericide. Increased organic content may consume more iodine or chlorine, also yielding more halocarbon residue. The Navy study did not use a bactericidal oxidant for their laundry water recycling scheme, but did use a bleach in the wash. A medical need for sterility of laundry water is not obvious. The only obvious access to the body of such residues is the use of washed handkerchiefs and dishtowels.

Significant water is evaporated, and shows up as condensate water. Lard et al. (3) find this as 5.6% (24 of 425 gallons) of the total laundry wash water, or about 1/4 of the final rinse water. A plausible target range for total dissolved solids (TDS) is 500-1000 ppM.

Hygiene wash - The second largest water use is washing persons and dishes. This water must be substantially pathogen- and toxin-free. Excess iodine or other bactericide can be tolerated, since the amount ingested by accident is surely small. Total dissolved solids (TDS) requirements are mild, assuming that adequate washing action is achieved. There is an advantage in maintaining at least marginal potability, since this water could serve as a backup in case of failure in the potable water supply. Here also water is lost to evaporation.

Other - Other water requirements are not well defined. If urinal flush water is only used to clean the collection device, filtered used shower water could be satisfactory, or even superior if residual detergent and bleach are present. Water for electrolysis, to produce hydrogen for reduction of respired carbon dioxide, has different quality requirements, since the presence of ions improves conductivity, reducing power losses, but some contaminants (e.g. sulfides) may poison catalytic electrodes. The first Working Group for the Space Station Freedom identified 0.2 to 0.4 pounds (mass, lbm) of hydrogen per person-day as required for the Bosch or Sabatier process for reduction of respired carbon dioxide (4). Some water is normally used for cleaning work surfaces. Water of many different levels of purity requirements may be required for experiments and process development space tasks.

| Uses | Hazard Sensitivities | | |
|---|---|---|---|
| | Inorganic | Organic | Biological |
| Potable | significant | significant | substantial |
| Laundry | slight | slight | slight |
| Hygiene-wash | slight | slight | slight |

**Implied water-quality requirements**

The water quality required for these needs can be individually analyzed for each need. The lowest quality requirements are for laundry water, where controls of pH, oxidation potential, conductivity, turbidity and total dissolved carbon are sufficient for satisfactory performance.

For bodily-contact hygiene water, higher standards (lower concentrations) are appropriate for these measured quantities. Standards for potable water are well established (JSC-SPEC-SD-W-0020, NASA STD-30000 and EPA 1986). Optimal compositions of desalinated water based on palatability as well as World Health Organization (WHO) standards have been proposed by Gabrielli (5,6).

An estimate of the principal air contaminants expected in a space station has been made by Yoshimura et al. (7) and is used later in this report to estimate organics condensing with water in the humidity control system. A more recent similar table was published by Leban and Wagner (8). For a selection of those of greatest concentration, threshold limit values (TLV) values from Verschueren (9) can be converted into allowed daily dosage (based on an 8-hour day, 5-day work week), and converted into the equivalent exposure in drinking water. These values are considerably higher than EPA maximum allowable concentrations (MAC) for priority pollutants for the general population. Some explanations are: (1) occupational limits may be at levels of the beginning of impairment, (2) the exposures are substantial for a limited time, (3) and for a small part of the population assumed in good health, (4) none of the major constituents are in the critical first Safe Drinking Water Act set.

In practice, one can distinguish and apply three independent criteria for water quality:

1) Toxic: exceeding this limit can incur performance degradation and short or long term health effects.

2) Risk: principally cancer. A risk "limit" depends on the risk level accepted. The selection of an acceptable risk level is influenced by:

a) the size of the population subject to risk,
b) comparison with other risk levels accepted, and
c) the personal standards of those individuals subject to risk.

3) Organoleptic: unpleasant or excessive taste or odor. Organoleptic levels may be temporarily exceeded without harm, but performance may suffer in extreme situations. Nausea may be exacerbated by an unpleasant taste or odor. This factor could be significant for hygiene and laundry waters insofar as odors are released to the air.

Probably the best poll of opinion of individuals subject to risk would be of former and present astronauts, as an estimate of the risk standards of future astronauts. One might ask if a risk level for exposure to cancer hazards in air and water might reasonably be 1% of the accepted cancer hazard from radiation, or some other value. For a large population, such as an eventual space colony, this level of risk could be lowered.

## RECLAMATION AND WATER QUALITY

### Distillation

A vapor-compression distillation (VCD) device has been evaluated for Space Station Freedom use (10). Some disadvantages of this distillation technique have been found, but its advantages are high water recovery, potentially good isolation from solute and biological contaminants, and ease of mechanical repairability.

Development at the Water Technology Center of the University of California, Berkeley, for the State of California Department of Water Resources resulted in substantial improvement in the overall heat-transfer coefficient between the condensing and evaporating films: this has considerably reduced the energy requirement of VCD. Designing the system as a multistage unit greatly increased the water output for a given heat input and aided in reaching a high concentration of brine in a continuous, rather than batch, process (11, 12). A multistage configuration uses the heat from condensing the first distillate to evaporate a second amount of wastewater: the temperature and pressure drops per stage are additive. Increasing the heat transfer coefficient by thinning the condensate water films decreases the temperature drop per stage, allowing more stages for a given temperature difference between the feed and the final condenser.

### Reverse osmosis

Recovery - Reverse osmosis (RO) is a hyperfiltration process involving high pressures (100 to 1000 psi) to press water through membranes designed to reject ionic and other larger species. It has been demonstrated to be appropriate for preparation of water for hygiene use and satisfactory as a source of potable water. Extraction of high-quality water from wash water containing of the order of 1000 ppM of total dissolved solids (13) can yield a 90% recovery, with a brine remaining of approximately 10 times that concentration. The brine could then pass to another process, such as oxidation of organics and/or distillation. To attempt a much higher recovery than 90% from such wash water presents the same problem as applying RO to water recovery from urine: higher pressures are required to overcome the osmotic pressure of a concentrated solution.

Permeability - Qualification of RO for extended use should include testing for extended periods with simulated or real washwater, since the plastics commonly used as membrane materials do have measurable permeabilities to organic solutes (14). The permeability of polymers to volatile organics can be turned to an advantage. A membrane selected on the basis of low porosity but appropriate solubility parameters, and thus impermeable to water, may allow permeation of organics in wastewater. In effect, this replaces the "air stripping" used in municipal water treatment but not possible in a confined atmosphere. Haxo et al. (15) give the following vapor transmission rates (VTR) of organic solvents and water passing through a 0.85 mm thickness of high-density polyethylene. Comparable data are also given for many other polymeric membrane materials.

| Solvent | VTR ($gm/m^2/day$) | From partial pressure (mm Hg) (23°C): |
|---|---|---|
| Water | 0.0472 | 10.53 |
| Methanol | 0.50 | 112 |
| Acetone | 2.19 | 212 |
| Cyclohexane | 151. | 89 |
| Xylene | 212. | 7 |
| Chloroform | 506. | 178 |

**Table 1. Vapor transmission rates through high-density polyethylene membranes.** (15)

### Electrodialysis

As a process that is electrically controllable and that operates at ambient temperature and pressure, electrodialysis (ED) is of interest for small desalination systems. It may be thought of as a self-regenerating ion-exchange-resin system, effective for removing ions but not organic solutes. Electrodialysis has been shown useful for further concentrating RO brines (16). At brine concentrations over 1%, the osmotic pressure to be overcome by pumping pressure becomes substantial in RO, while in the same concentration range for electrodialysis the increasing solution conductivity substantially reduces electrical power loss.

### Ion exchange

A traditional use of ion exchange in water treatment has been for water softening, not needed in most water recycling. However the water softening process works by means of a useful effect: in dilute solutions polyvalent ions (calcium or magnesium in water softening) bind to a cation-exchange resin much more strongly than do monovalent ions: thus the resin releases sodium in exchange for calcium. Most of the potentially toxic heavy-metal ions of concern here are polyvalent (e.g. $Cr^{+3}$), and so are even more strongly bound than calcium. By careful choice from the many resins commercially available, including chelating resins, a guard column or cartridge can be tailored to the needs of the mission. Prediction of resin-water equilibria in the presence of several ionic species can be performed by the method of Klein (17); for use on small computers the Klein program has been revised into BASIC (18).

### Carbon adsorption

Removing organic constituents, even at trace levels, is accomplished with activated carbon. Regeneration is a thermal process: desorbed gases must be vented or, preferably, oxidized. Oxidation could be performed if the adsorbates could be desorbed into an air stream supplying a solid- or liquid-waste oxidation processor. Removal capacities for many compounds are in the range of 100 mg per gram of carbon (19), but some volatile compounds of importance (e. g. methanol) are poorly adsorbed, and are retained only at loadings of the order of 10 mg per gram of carbon, (20: Table 17.2). An estimate of the amounts of organics to be removed from the water streams is necessary in order to choose the size of activated-carbon cartridges and to determine the need for and frequency of regeneration.

### Other

Reports from development of supercritical water oxidation equipment for waste disposal (21) indicate that this may be a substantial source of water for recycling. Product sterility is certainly assured. Inorganic content is predicted to be low, from the insolubility of ionic compounds in the supercritical phase. A recent publication on this project indicates that further development is needed (22).

A convenience for future spacecraft missions incorporating food production using higher plants is that the supercritical oxidation process with minor modification can yield a nutrient water for growing plants, with nitrogen retained as ammonia (23) and inorganic nutrients redissolved on removal from the supercritical condition.

At first glance, an electrochemical oxidation proposed (24) does not seem competitive with the wet oxidation method, in that power is consumed in generating the oxidant electrochemically (25: p. 42). However, as much or more power may be required to make the oxygen consumed by any other oxidation process.

### Bactericides

Bacteria can thrive in most water, so safety can never be assumed. Bacterial growth should be prevented even in the humidity condenser, which is poorly accessible to additions of disinfectants. One approach might be to add a volatile oxidizing agent as bactericide at the entrance to the condenser.

Sterility of final-product potable water must be separately assured. Concern has been expressed (26, 27) about the accumulation of iodide in water treated with enough iodine to maintain bactericidal activity during storage. Since iodine is readily formed by electrochemical oxidation of iodide, electrochemically recycling the reduced iodide to iodine would seem possible. In the low conductivity of potable water this would not be a rapid reaction, but if stored water is slowly circulated past the oxidizing electrode, disinfectant activity may be maintained with a small dosage of iodine.

Competitive oxidants can be prepared electrochemically as required: chlorine, hydrogen peroxide and/or ozone. The destruction of viruses by ozone is more rapid than by chlorine (28), which may be advantageous in the small water treatment module. Better taste and lack of halocarbon formation are additional advantages. Gnann (29) has found optimum ozone production to require an electrochemical cell with a concentrated phosphate buffer containing fluoride and cooling.

## PERFORMANCE CHOICES

A first example is a simple configuration for water recycling. A second example indicates how process options can be applied. Such examples provide an opportunity to examine the means for trapping identified hazards and to search for failure modes.

**Example 1**

Flow choices - One configuration satisfying the criteria is shown in Figure 1. Humid air from the crew's respiration and from evaporation of washwater arrives at the condenser. Product water from $CO_2$ reduction is of high quality and can add to condensate water or to hygiene-wash, as needed. Initially it will be assumed that a particulate filter is not required, but that a carbon filter is, probably lightly charged with iodine. A cation-exchange resin is included to trap most inadvertent metals. A few ppM of calcium bicarbonate are added to improve taste, lower corrosiveness, and buffer pH (5, 6).

Washing-quality hygiene water comes from wash water recycled through RO or distillation. A carbon filter should be sufficient protection for this stream: very little bodily exposure to hazardous ions exists. Electrochemical chlorination (chloride in the RO brine, originating from sweat, is oxidized to chlorine) or ozonation might be more convenient than iodination, and appropriate if the source of this water is more subject to bacterial contamination. A field-shower recycling study (30) implied that high-quality water is not needed here, but the advantage of having an emergency source of potable water, combined with the potential inconvenience of transmission of disease or toxins through inadvertent access to the body led to the recommendation of RO or distillation purification here, with simpler treatment being applied to the more major water use that follows.

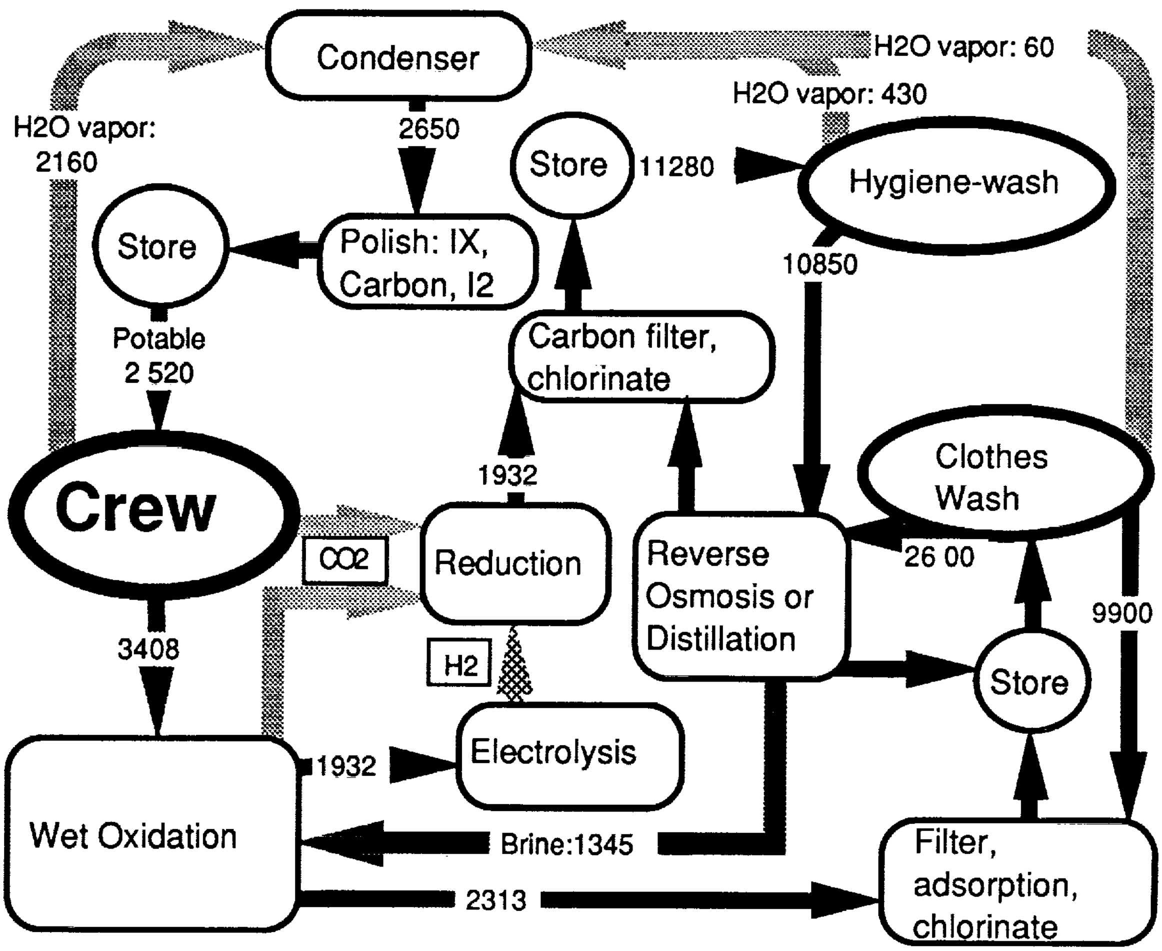


**Figure 1. Closed-loop water treatment example 1.** Values in grams/person-day.

In this minimum example clothes-wash water is filtered, and organics may be partially removed through adsorption. Wet-oxidation water is of good quality, so it is added in the final rinse to compensate for evaporation losses. Electrochemical chlorination or ozonation is appropriate if this water is likely to be contaminated by bacteria. Monitoring conductivity is appropriate: a fraction of this water on exceeding 1000 ppM should be passed for purification to the RO (or distillation) process. This also makes up for evaporation losses in the hygiene-water cycle.

Spreadsheet analysis - This Example 1 and other performance examples can be tested for mass balance by spreadsheet analysis as in Table 2. The amounts of each source water (named in the first column) are estimated in column 2, passed through treatments in the next column, to product water. The percentage of total of estimated user needs is in the last column.

| Source | Grams/ person-day | Process RO factors: | Output1 0.90 | Brine 0.10 | Out TDS (initial) | (ppM) (final)* | User Needs |
|---|---|---|---|---|---|---|---|
| Clothes | 2600 | R O | 2340 | 260 | 25 | 168 | Potable |
| wash | 9900 | Filter | 9900 | | 116 | 730 | 2520 |
| Hand+shower | 5450 | R O | 4903 | 545 | 163 | 163 | |
| wash | | | | | | | Semi-Potable |
| Dishes | 5400 | R O | 4859 | 540 | 88 | 88 | 10896 |
| wash | | | | | | | |
| Total Hygiene | 23350 | | 22001 | 1345 | 111 | 402 | Wash Only 12984 |
| Urine | 1568 | | | | | | |
| Urine flush | 494 | add Urine | 2062 | | 21996 | 22066 | |
| Trash+Feces+ | 1346 | | | | | | |
| Urine Out+ | 4753 | Wetox | 4245 | 85 | 1309 | 1320 | |
| RO Brines | | | | | | | |
| Cabin air | 2650 | condense | 2650 | | 160 | 160 | |
| Humidities | | | | | | | Electrolysis |
| CO2 Redctn | 818 | Bosch | 1932 | includes | wetox.CO2 | | 1932 |

**Table 2. Wastewater sources, processing and water needs comparison.** Values are grams per person-day. Water sources and use estimates from Wydeven and Golub (31) and references cited therein. RO and wet oxidation rejections are preliminary estimates.
(*) Concentration reached with recycle of 70% filtered, 30% RO, clothes-wash water, after ca. 100 cycles.

Simulations - Overall tests of the water reclamation system and estimates of constituent/contaminant flows and changes under various possible and extreme conditions may be made by computer simulations of the processing elements. The elements may then be linked to simulate an entire water cycle. Where products and starting compositions are known from tests, the simulation can be reviewed for accuracy of representation.

The humidity-condensation process was simulated first. The objectives were to estimate the contaminants expected in water condensed from air, the contaminants removed by this means, and the requirements for and best locations of activated carbon (in the inlet air stream, in the outlet air stream, or in the water stream).

The condensation process has as the input vapor: Air, temperature $22^{o}$ C, relative humidity 50% = 13 ppT water, and $CO_2$ at 400 ppM. A resulting water phase is the amount of condensate in equilibrium with the air: the latent water from cabin air, 2650 g/person-day (32). An estimate of the principal air contaminants expected in a space station (14) is given, for the principal constituents in descending order, in the first two columns of Table 3, for a crew of two (32). The calculated concentrations at a cabin flow of 25 $m^3$/hr are in the third column. A simulation calculation of the amount dissolving in the condensate water yields the contaminant concentrations of the next columns.

If the constituents are trapped by activated carbon from the air phase assuming a "ventilation" rate of 10 exchanges per day, the concentrations of the 6th column are obtained. At the rate identified by Otsuji and Yoshimura (5 exchanges per day), results in the 5th column are obtained. A more recent table is given by Leban and Wagner (8). This lists metabolic generation rates and Space Station Freedom generation rates, in comparison with Spacecraft Maximum Allowable Concentrations derived from occupational exposure values.

| Constituent | Cabin-Air amount, per person of 2-person JEM (mg/day) | Air concentration, (ng/liter) | 1/day | Water, after condensing (mg/liter) 5 exch. | 10 exch. | MAC |
|---|---|---|---|---|---|---|
| Dichloromethane | 1126. | 3.75 | 218. | 43.6 | 21.8 | |
| Butanol-1 | 977. | 3.26 | 412. | 82.5 | 41.2 | |
| Ethanol | 654. | 2.18 | 249. | 49.9 | 24.9 | |
| m-Xylene | 629. | 2.10 | 265. | 53.0 | 26.5 | 10. |
| Methyl ethyl ketone | 620. | 2.06 | 215. | 43.1 | 21.5 | |
| Acetone | 526. | 1.75 | 139. | 27.9 | 14.0 | |
| Propyl acetate | 336. | 1.12 | 140. | 26.7 | 13.4 | |
| Methyl isobutyl ketone | 258. | 0.86 | 106. | 21.2 | 10.6 | |
| Propanol-2 | 254. | 0.85 | 100. | 20.0 | 10.0 | |
| Ammonia | 238. | 0.79 | 86. | 19.4** | 9.9* | 0.5 |
| Carbon monoxide | 219. | 0.73 | 0.02 | 0.00 | 0.00 | |
| Butanal | 194. | 0.65 | 66. | 13.1 | 6.6 | |
| Cyclohexane | 194. | 0.65 | 66. | 13.3 | 6.7 | |
| Toluene | 170. | 0.57 | 66. | 13.6 | 6.8 | 2. |
| Cyclohexanol | 164. | 0.55 | 70. | 14.0 | 7.0 | |
| Total organics | 6382. | 21.3 | 2114. | 421.9 | 211. | |

*includes 9.1 as ammonium bicarbonate plus 0.61 as ammonium acetate. pH=8.1.
**includes 17.4 as ammonium bicarbonate plus 1.21 as ammonium acetate. pH=8.3.

**Table 3. Simulated Contaminant Carry-over in Humidity-condensation Process.** Data from Yoshimura (7) used in PROCESS simulation program.

**Example 2.**

Supercritical wet oxidation is a step that remains under evaluation. While a competing electrochemical oxidation process (33, 24) has also not yet been proved satisfactory for dependable use in space, for a second example of an oxidation step it makes an interesting other approach. It is of some additional interest in that hydrogen evolved from the non-oxidizing electrode can be used for the $CO_2$ reduction process, providing an economy of operations. Some ozone and/or chlorine may be evolved, of possible use in sterilizing final product water.

We will suppose that the process cannot be relied upon completely to provide potable or even semipotable water, but that sterility can be assured by the oxidizing electrode and that enough of the organic content of the washwaters and urine is destroyed so that product water can be returned as input to a reverse-osmosis unit. Some indestructible material will accumulate as brine recycling between the electrolysis and RO units, so a true waste stream is generated.

Removal of ionic waste is satisfied by an electrodialysis concentrating compartment included in the electrolysis cell. (The current density required for oxidation may exceed that allowed for electrodialysis, so this figure may be oversimplified.) The concentration of the ED brine is chosen by adjustment of the drain. This now multifunctional electrolysis cell is drawn in Figure 2.

Figure 3 is a diagram of this water-recycling configuration. Most of the elements are similar to those of the first example, except for restructuring the electrolysis module to include oxidizing and brine-concentrating functions. For this example the RO module has been increased in size to include all the clothes-wash wastewater, as another significant option.

## SUMMARY AND RECOMMENDATIONS

A basic water recycling system to provide and assure quality of potable water, hygiene-wash water, and laundry water has been described. Assurance of performance relies on simplicity, redundancy, and in-flight repairability. Water-quality assurance relies on choices of source waters, redundant monitoring, and, through monitoring, a means for failure analysis.

The development route is clear, leading to qualification of all devices needed for assurance of water quality in a system for recycling 90% or more of spacecraft human needs. 100% of water requirements can be reached if water chemically bound in trash materials is recovered by a waste-oxidation process.

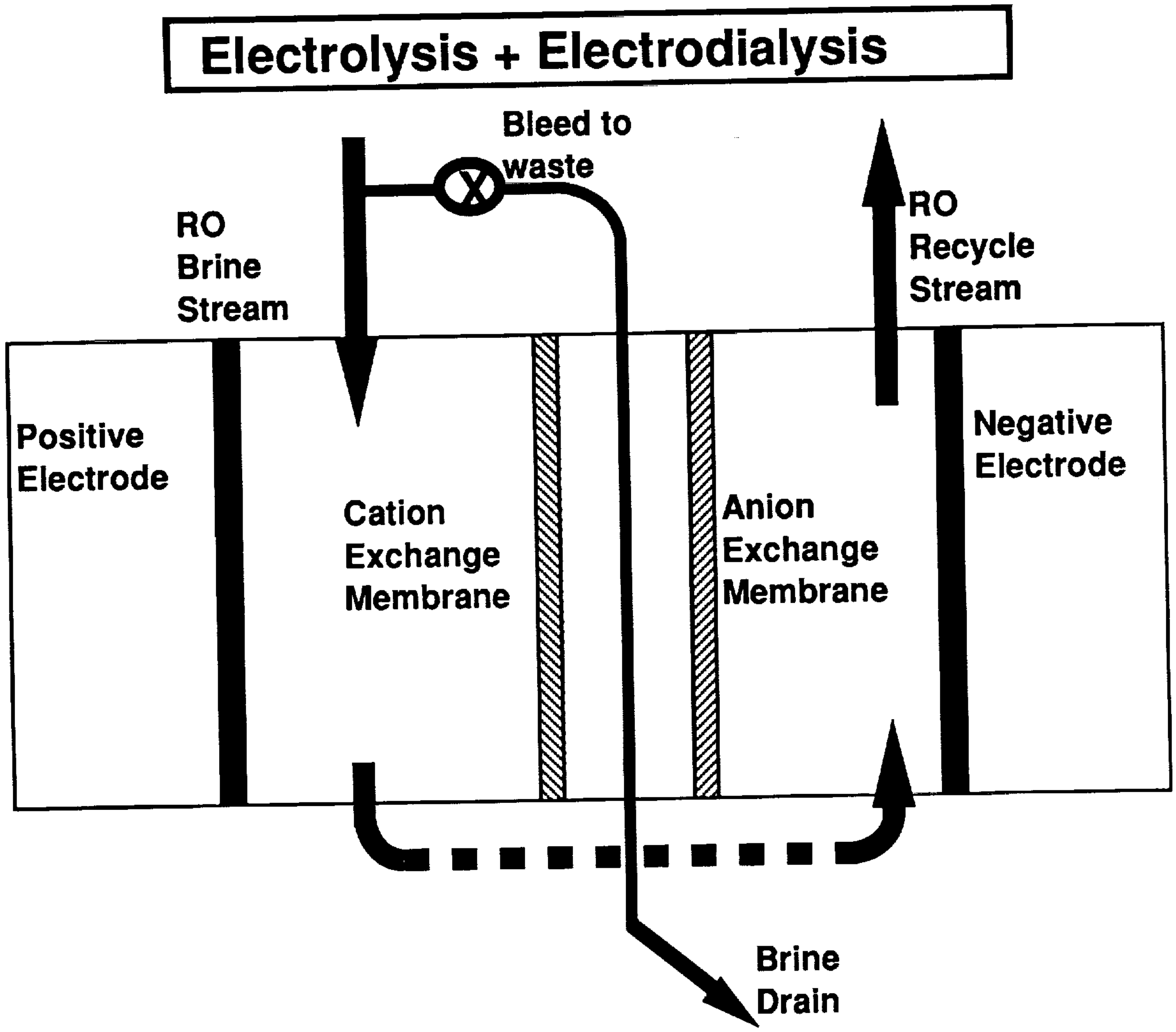


**Figure 2. Combined Electrolytic Cell of Example 2.** Organic contaminants of RO reject brine are supposed incompletely oxidized by the positive electrode: some gas ($CO_2$ and $O_2$) will be evolved and centrifugally separated. Some hydrogen will be evolved at the negative electrode, for use by the Bosch reduction process. Ionic constituents are further concentrated by passage through ion-exchange membranes, as conventional electrodialysis.

Critical decisions - Decisions necessary for specification of water recycling and water quality assurance equipment are in part externally determined by definitions of mission, crew requirements and construction materials, and in part by definitions of water-treatment processes. Spacecraft and habitat environmental temperature and pressure choices also influence the water cycle, and so are to be included in whole-system simulations. Several values external to the water-processing system, but influencing its performance, are required as input data to obtain realistic predictions of water quality as a function of process choices. These include: Accurate specification of water volume and time-of-use requirements for the mission, availability of waste heat, as from electronic components, medical specification of levels for additives to potable water: fluoride, calcium, bactericide.

Material choices of plastic or metal spacecraft components significantly influence the needs for contaminant-trapping. Final decisions on the size and type of contaminant traps require (1) that results of current toxicological research be followed for new information on hazards and limits, and (2) that components of the spacecraft that can directly or indirectly contact the water supply be characterized as soon as selected, for normal degassing and corrosion products and also decomposition and corrosion products of failure modes' (e.g. overheating) . It is not implied that materials should automatically be excluded for degradation potential, since in most cases adequate control of degradation products can be provided.

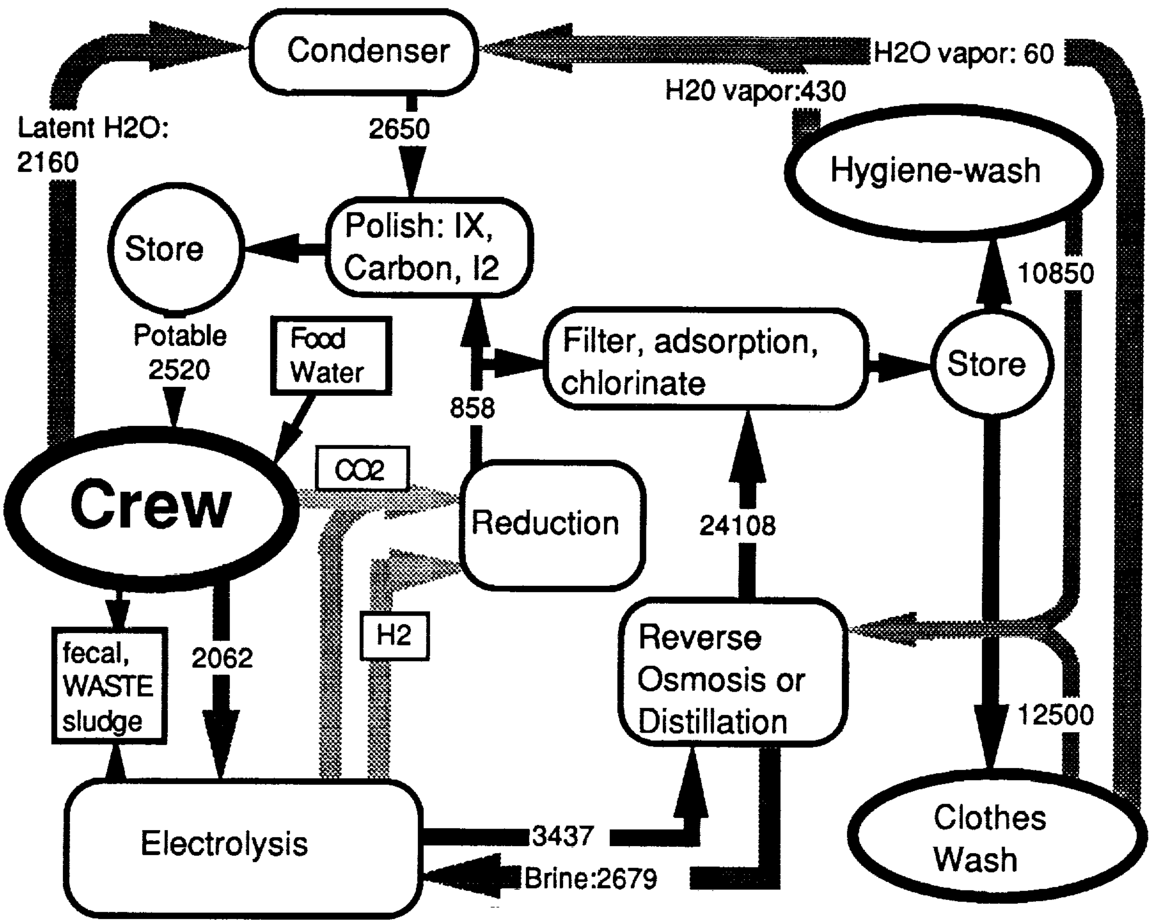


**Figure 3. Example 2: Closed-Loop Water Supply.**

The most critical water-system decisions are seen as: oxidation method (supercritical wet oxidation vs. other), water purification (RO vs distillation), and impurity trapping (ion exchange and carbon adequacy). These choices are to be made on the basis of recommended testing.

The method applied here, analysis of wastewater sources and water needs, followed by choice and adaptation of technology, aand optimization using chemical process simulations by computer, can be applied to many industrial and home situations, where recycling can provide both safe disposal and reliable supply.

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